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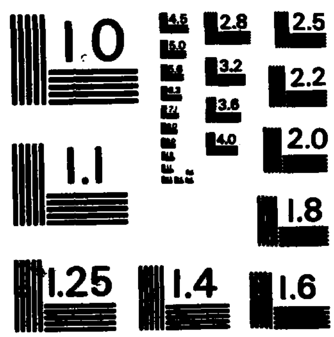

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UNSTEADY FLOW OVER AEROFOILS WITH SEPARATION

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20. Abstract

The mean and fluctuating components of surface pressure and lift have been measured on a NACA 0012 aerofoil in an unsteady flow gust tunnel giving a mean flow with streamwise fluctuations of variable amplitude and frequency. The tests were carried out for a range of aerofoil incidences from 10° (attached flow) to 20° (separated flow) at a mean chord Reynolds number of 1.2×10^{5}. Some comparisons of the results are made with unsteady aerofoil theory.

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SUMMARY/PREFACE

This report describes work carried out by the author at the Hermann-Foettinger Institute, Technical University of Berlin, under AFOSR contract number 81-0050 during three visits in September 1981, April 1982 and September 1982.

Experimental measurements of the mean and fluctuating components of surface pressure and lift were obtained for a NACA 0012 aerofoil in an unsteady flow 'gust' tunnel. This wind tunnel provided a mean air stream with superimposed streamwise fluctuations whose amplitude and frequency could be varied. The aerofoil was tested over a range of incidences from 10° for which the flow was fully attached to 20° for which it was fully separated. Because of the limitations imposed by the size of the working section of the wind tunnel (0.5 m (1.64 ft) square) and the acoustic output from this type of flow the measurements were limited to a low chord Reynolds number of 1.2×10^{5}.

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LIST OF ABBREVIATIONS AND SYMBOLS

a_o	Lift curve slope $\partial C_L/\partial\alpha$
c	Aerofoil chord
C_p	Pressure coefficient $p/\frac{1}{2}\rho\bar{U}^2$
C_L	Section lift coefficient $L/\frac{1}{2}\rho\bar{U}^2c$
f	Cyclic frequency
J_n, Y_n	Bessel functions of order n
k	Reduced frequency $\omega c/2\bar{U}$
L	Lift
p	Static pressure
R	Reynolds number based on chord $\bar{U}c/\nu$
t	Time, T cycle period
U	Total streamwise velocity
u	Fluctuating component of streamwise velocity
x	Streamwise coordinate, origin at the leading edge
δy	Distance above aerofoil surface, measured normally
α	Incidence of aerofoil
λ	Wavelength
ν	Kinematic viscosity of fluid
ρ	Density of fluid
ω	Radian frequency
p.s.i.	Pounds per square inch
R.M.S.	Root mean square
$-$	Overbar indicating time mean

1. PURPOSE AND SCOPE OF INVESTIGATION

The experimental work described in this report forms a continuation of work carried out during an earlier period under the sponsorship of a NATO research grant (No. 1554). In this earlier programme the gust tunnel at the Hermann Foettinger Institute in Berlin (which is of the open circuit type with a fan at the donstream end), was calibrated by making detailed measurements of flow velocity and wall pressures over a range of wind speeds and gust frequencies.

The gust tunnel provides a mean flow up to about 20 m/s (65 ft/s) with superimposed streamwise fluctuations generated by a set of rotating vanes at the downstream end. The amplitude of the unsteady fluctuations range from a maximum of 100% of the mean flow at low speeds and frequencies with more typical amplitude ratios up to 25% over a range of frequencies up to 50 Hz. More details of the wind tunnel and a method of tuning it in order to obtain sinusoidal velocity fluctuations are described in (1). Figure 1 shows the arrangement of the tunnel and its working section.

After the initial calibrations of the flow, two sets of measurements of the unsteady forces induced on aerofoils in this flow were made. In the first of these, direct measurements of the mean and fluctuating lift force (using piezo-electric transducers) were made on a NACA 0015 aerofoil set at an incidence below the stall, over a range of gust frequencies. This experiment verified that satisfactory agreement could be obtained for the unstalled fluctuating lift with the predictions of unsteady thin aerofoil theory. In the second series of tests some preliminary measurements of the fluctuating surface pressures on a NACA 0012 aerofoil set at incidences 10^o, 12.5^o and 20^o to the airstream were made

In the present research programme described in this report the measurements of unsteady surface pressure on the NACA 0012 aerofoil were extended to cover a wider range of incidence and unsteady flow parameters. In addition a new piezo-electric lift balance with improved resonance characteristics was constructed incorporating a light, stiff NACA 0012 aerofoil of carbon fibre skin construction. This aerofoil had the same chord as the one used for surface pressure measurements. The NACA 0012 profile was selected for this investigation because of its importance in unsteady flows, particularly as a helicopter blade section. The aerofoils were set at mean incidences from 10^o to 20^o in the working section of the wind tunnel and subjected to periodic flows of fluctuating streamwise velocity with approximately sinusoidal variation:

$$U(t) = \bar{U} + u \sin \omega t.$$

The purpose of this investigation was to obtain predictions of the unsteady loads induced on aerofoils at incidences above the stall angle by streamwise fluctuations of the flow. Investigations of this type are limited to

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(1) "A wind tunnel for unsteady turbulent shear flows: design and flow calculations," by H.H. Fernholz, J.M.R. Graham and J.-D. Vagt. To be published in Zeitschrift für Flugwissenschaften und Weltraumforschung (ZFW).

low Reynolds numbers (generally of the order of 10^5) because of the large amount of acoustic power radiated by such flows except at very low frequencies. However there is some evidence (2) that separated unsteady flows of this type are less sensitive to Reynolds number than are separated flows over aerofoils in steady streams. In addition it was intended that pressure measurements and flow visualization might indicate the fundamental mechanisms occurring in this type of separated flow. A great deal of work has been carried out in the case of unsteady separated flow caused by an aerofoil performing pitching oscillations in a steady airstream, for example (3). These have shown that a major mechanism occurring in such cases is the periodic shedding of a concentrated vortex from near the leading edge. The convection of this vortex, usually at about half the free stream speed, over the suction surface of the aerofoil leads to large increases in lift and pitching moment. It was hoped that the present measurements might reveal whether a similar phenomenon occurred in the case of an aerofoil at fixed incidence performing streamwise oscillations or as in this case in a free stream with an oscillatory streamwise gust superposed.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

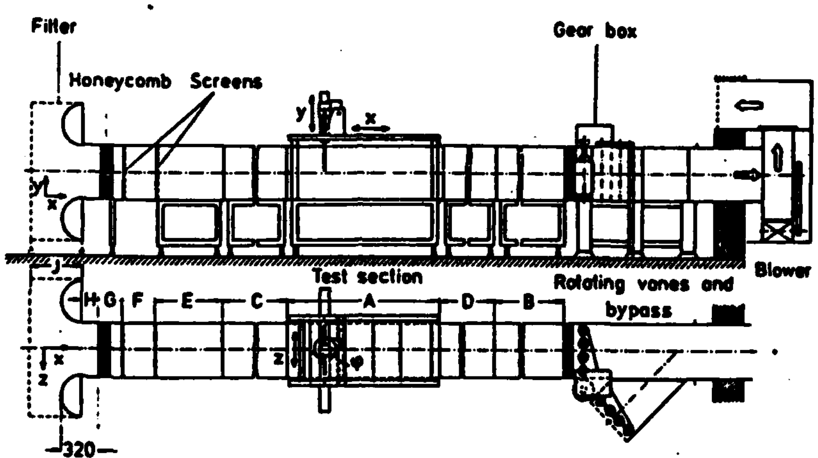
2.1 Description of Unsteady Wind Tunnel and Flow. The open circuit wind tunnel is of a constant 0.5 (1.64 ft) square cross-section with a centrifugal fan at the downstream end and a set of rotatable profiled vanes just ahead of the fan, see Figure 1. Rotation of these vanes provides an oscillatory velocity and pressure field at twice the vane frequency throughout the length of the tunnel, superimposed on a mean velocity. The velocity field in the tunnel was measured by means of a previously calibrated, linearised, constant temperature, hot-wire probe; the pressure field by capacitance microphones of the diaphragm type flush mounted in the side walls of the tunnel. After fitting the tunnel with a profiled intake, wire screens and honeycomb the R.M.S. free stream turbulence level in the tunnel was reduced to about 0.9%. Measurements of the velocity (u) and pressure (p) fields of the flow showed them to be closely represented by the components of an acoustic wave related by

$$\bar{\rho}\,\frac{\partial u}{\partial t} \simeq -\frac{\partial p}{\partial x}\,. \qquad (1)$$

This wave had a pressure node a short distance outside the intake plane of the tunnel and was composed of a fundamental at twice the vane frequency and a number of higher harmonics of varying power. Because of the acoustic nature of the flow it was possible to tune the length of the wind tunnel to a quarter wavelength at the desired fundamental frequency and eliminate most of the power in the higher harmonics thus producing a fairly sinusoidal velocity oscillation. This procedure was used for the

(2) Saxena, L.S., Fejer, A.A. and Morkovin, M.V. Features of unsteady flow over airfoils. AGARD C.P. 227 Paper No. 22, 1978.

(3) McCroskey, W.J., Carr, L.W. and McAlister, K.W. Dynamic stall experiments on oscillating airfoils. AIAA Journal, Vol.14, p57, 1976.



Length of tunnel sections in mm			
A	1725	F	300
B	1440	G	200
C	1400	H	320
D	1000	J	700
E	600		

FIGURE 1

Sketch showing main dimensions of open circuit suck-down tunnel with rotating vanes tests described here with the measurement plane at the half distance along the wind tunnel. In this configuration a typical velocity fluctuation shown in Figure 2 could be obtained. The static pressure level at the measurement plane was also fluctuating with time according to equation (1) and this fluctuation was subtracted from the measured pressures. Since the variation in pressure and velocity over the aerofoil chord was very small at all the frequencies used it was neglected and the acoustic pressure field treated as imposing passive fluctuations of level.

For the reason of limiting the acoustic power radiated into the laboratory the tests were carried out at a mean flow velocity of approximately 12 m/s (40 ft/s). The maximum amplitude of oscillation used was 17% of the free stream (mean to peak) and the maximum oscillation frequency 25 Hz. The amplitude produced by a given vane setting decreased with increasing frequency.

2.2 Direct Measurements of Unsteady Lift on the Aerofoil. A NACA 0012 aerofoil with a chord of 0.15 m (0.49 ft) and a span of 0.47 m (1.54 ft) was mounted on two piezo-electric elements as shown in Figure 3. The elements were constructed to remove unwanted signals arising from torque and shear forces and to only respond to forces along a prescribed axis of the element. The aerofoil was manufactured from a hollow carbon fibre construction to give as high a natural frequency as possible (260 Hz approx). The output signals from the piezo-electric transducers were summed and amplified to give a voltage proportional to the overall lift force, checked by calibration with known weights. The signal was filtered to remove noise and by careful setting up the D.C. drift due to charge leakage was reduced to less than 1% of the full scale voltage per hour thus allowing mean measurements of lift to be obtained with reasonable accuracy. The piezo-electric elements were mounted in the end plates of the aerofoil which isolated the aerofoil from the side wall boundary layers of the wind tunnel. There was a small gap of approximately 1 mm between each end plate and the aerofoil. The plates had a chord equal to twice that of the aerofoil and ran the full depth of the working section, being supported from the roof which was as far as possible isolated from the vibrations of the fan and vanes. The apparatus was tested with the aerofoil at zero incidence. The noise signal in the absence of lift was very small at low frequency rising to about 10% of a typical lift output at 25 Hz.

2.3 Measurements of Unsteady Pressures on the Aerofoil. The measurements were made on an aerofoil machined from duraluminium alloy with the same profile and chord as the aerofoil used for the lift measurements, the span being very slightly larger (0.48 m, 1.57 ft). This aerofoil was fitted with a SETRA ±0.1 psi differential pressure transducer of the capacitance diaphragm type inside a cavity in the aerofoil. The transducer was aligned because of its size in the spanwise direction and connected to a line of pressure holes along the midspan of the upper surface of the aerofoil from the leading edge to 87% of the chord. These pressure tappings were connected individually to the transducer cavity by plugging the other tappings. Because of the distance between the furthest tappings and the transducer (about 0.5 chord) and the Helmholz resonance effect, this system could not measure reliably at frequencies above about 80 Hz. However the sensitivity and accuracy of this type of transducer were felt to outweigh the disadvantages caused by its size.

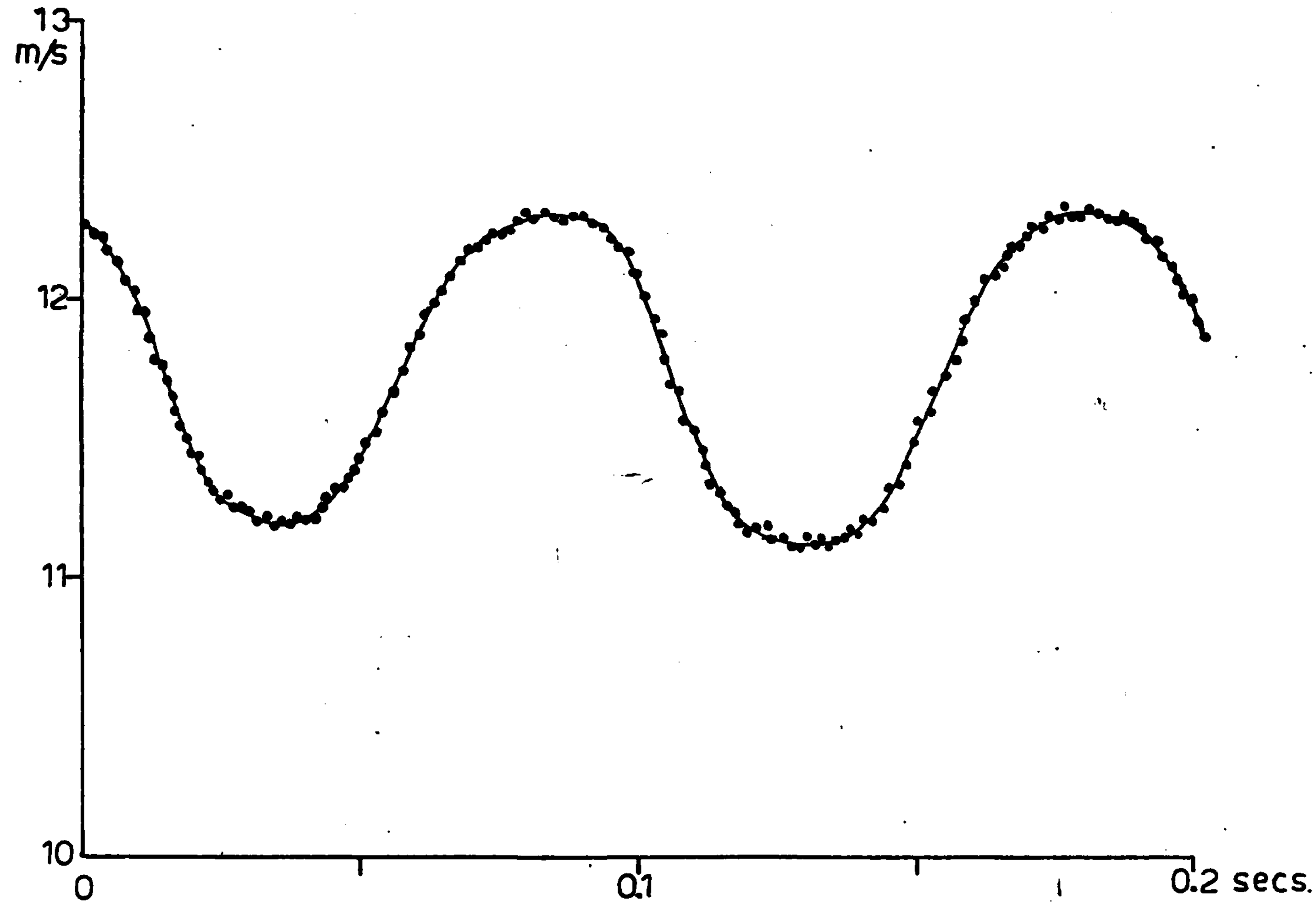


FIGURE 2 Fluctuating velocity at aerofoil position.

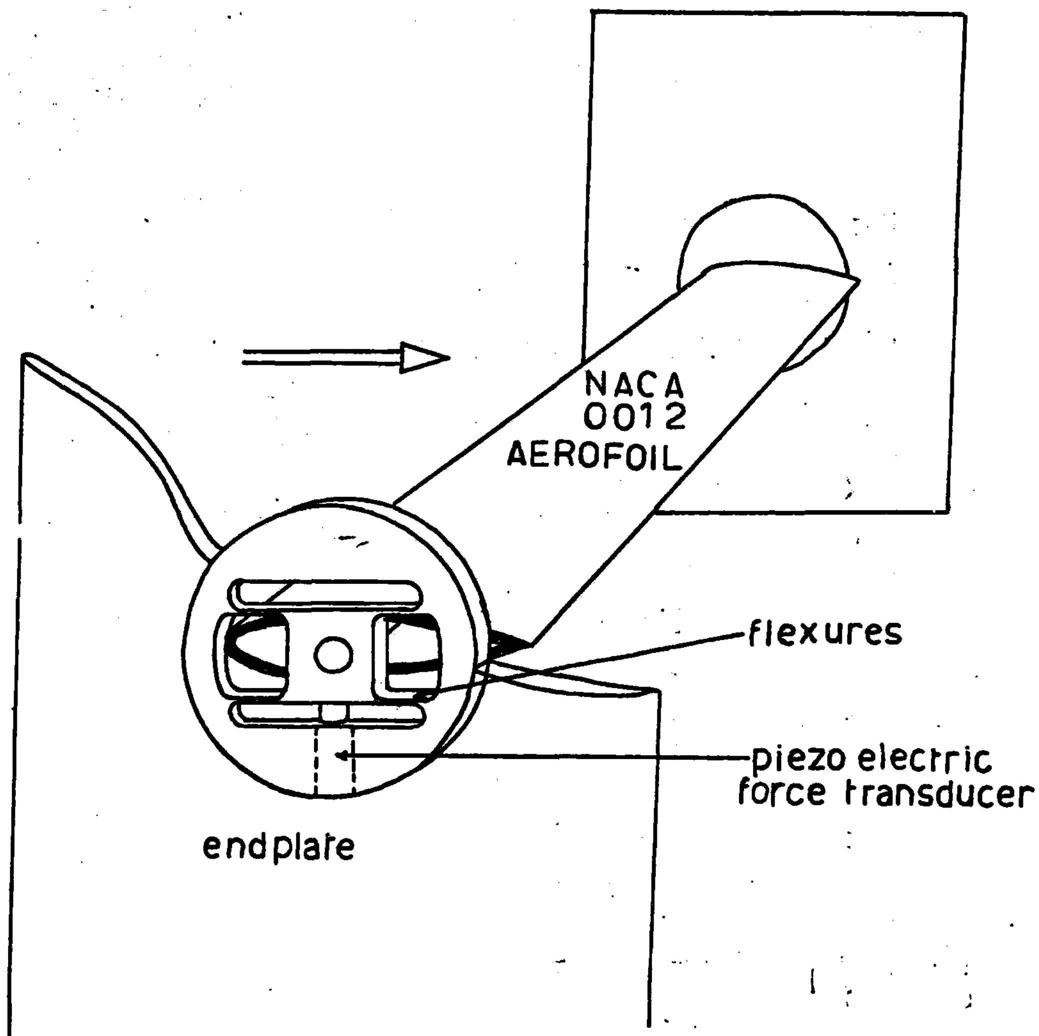


FIGURE 3 Layout of aerofoil and piezo-electric force transducers.

Pressure measurements were therefore made at different times for different points on the aerofoil surface and could only be combined for purposes such as integration to obtain the overall lift by some form of cyclic averaging. In the case of attached flow and most of the unsteady separated flows the flow was found to be quite periodic with only small variations from cycle to cycle. In these cases a meaningful average cycle could be defined and individual pressures combined. However in some cases, particularly close to the stalling incidence the pressures and loads showed large fairly random fluctuations from cycle to cycle and straightforward cycle averaging was not possible. In these cases an attempt was made to set up a system of conditional averaging.

Lower surface pressure measurements were obtained for this symmetric aerofoil on the centre-line of the wind tunnel by reversing its incidence to the flow.

2.4 Cycle Averaging Procedure. The output from the load, pressure (or any other) transducer in the gust tunnel could be sampled at a predetermined rate and input via an analog to digital converter to a Hewlett Packard computer which was located in the Institute. Using a two channel input it was possible to take a voltage output from the wind tunnel vanes, in the form of a succession of square waves which could be used as the reference signal for each cycle. A computer program was written to perform cycle averages by this method. Figure 4 gives an example of an averaged cycle obtained by averaging over different numbers of consecutive cycles showing the ergodicity of the signal (in this case lift).

In those cases where the signal was more random it was found by a number of trial experiments that there was a good correlation between the peak of the velocity trace measured at the point $x = 0.053c$, at a height $\delta y = 0.015c$ just above the aerofoil surface behind the separation point, and the load or pressure signals. This correlation occurred because a velocity measurement at this position was intersected by the separating shear layer for some cycles and not others according to the behaviour of this shear layer which also controlled the lift and pressure on the aerofoil. A computer program was written to perform conditional averaging based on this criterion and was tested for one particular case.

All free stream velocity measurements to which the lift and pressure measurements are referred at any given vane setting were obtained with a hot wire probe placed at the position of the quarter chord of the aerofoil in the empty working section. The results given in this report have been corrected for wind tunnel blockage (4) but correction procedures for unsteady incident flows have not been fully established.

2.5 Flow Visualization. Two types of flow visualization were carried out. In the first smoke consisting of condensed oil vapour was emitted from a small tube just upstream of the aerofoil (Figure 5). The smoke was illuminated by a beam of light from a 5 watt laser swept through the flow field by a rotating mirror. The rate of rotation of this mirror was sufficiently high to keep phase lags in the resulting pictures of the smoke to within a few degrees. In order to obtain high density smoke pictures these tests were carried out at reduced velocities and hence Reynolds numbers (in the range 0.2×10^5 to 0.8×10^5).

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(4) Garner, H.C., Rogers, E.W.W., Acum, W.E.A. and Maskell, E.C. Subsonic wind tunnel wall corrections. AGARDograph 109, 1966.

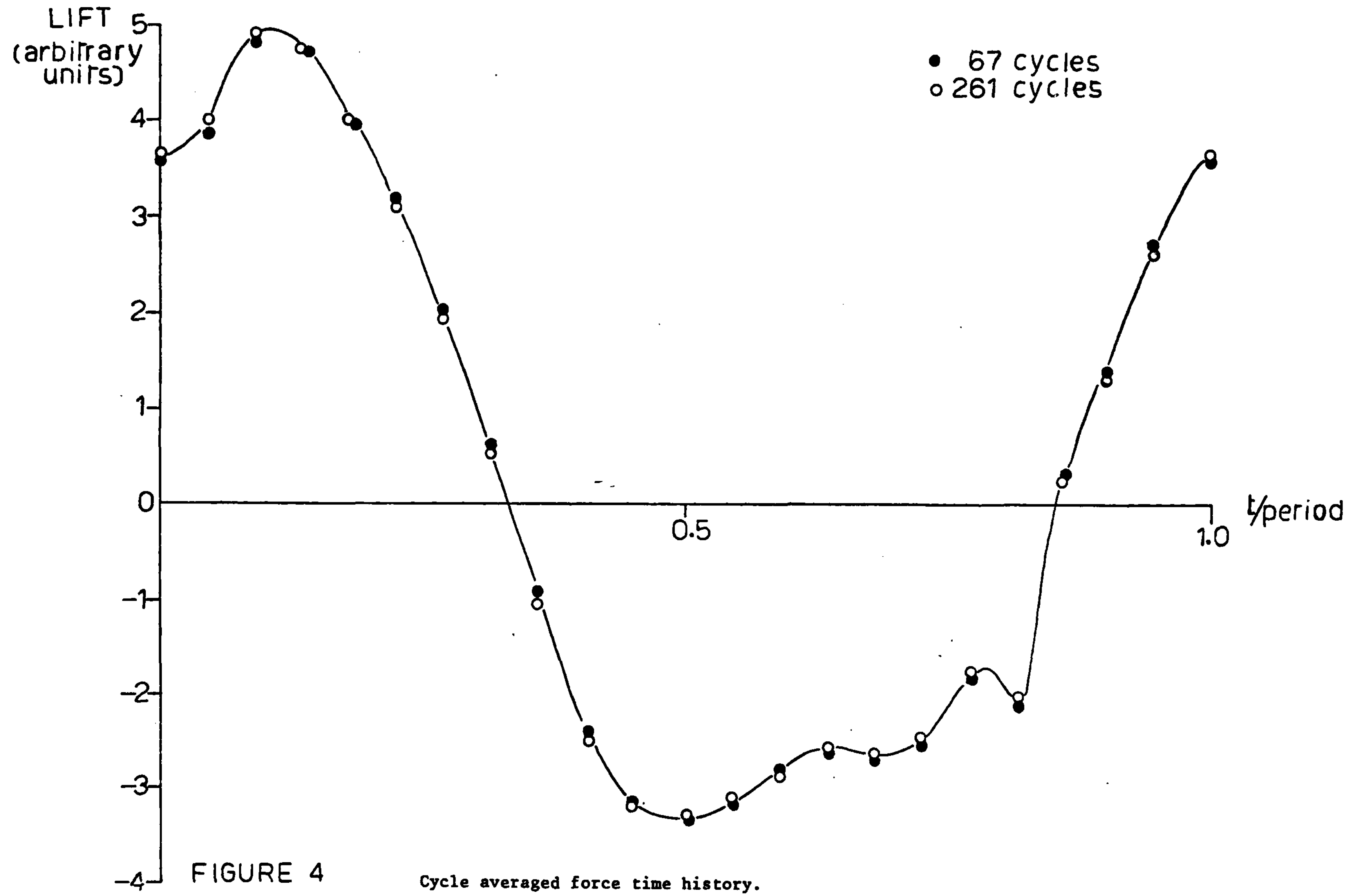

FIGURE 4 Cycle averaged force time history.

FIGURE 5

Smoke flow over the aerofoil at 15° incidence, $k = 1.3$, $Re = 0.4 \times 10^5$.

The second flow visualization technique was that of painting the upper (suction) surface of the aerofoil with a mixture of parafin oil chalk and titanium oxide in order to determine the position of the separation line on the aerofoil. These tests were run at the same mean chord Reynolds numbers as the force and pressure measurements.

3. UNSTEADY THIN AEROFOIL THEORY FOR STREAMWISE OSCILLATIONS AND UNSEPARATED FLOW

A version of unsteady thin aerofoil theory has been developed by Morfey (5) for the case of a streamwise convected, sinusoidal gust

$$U = \bar{U} + \hat{u}\, e^{i(\omega t - \lambda x)}, \quad (\omega = \lambda \bar{U}),$$

passing an aerofoil at incidence α to the flow. In this case the lift coefficient is given by

$$C_L = 2\pi\alpha\left[1 + \hat{u}/\bar{U}(S(k) + J_o(k) + i\,J_1(k))\, e^{i\omega t}\right] \tag{2}$$

where $S(k)$ is the Sear's function for a convected transverse sinusoidal gust and k, the reduced frequency $= \omega c/2\bar{U}$.

This analysis can be extended to the approximately homogeneous oscillatory streamwise flow $U = \bar{U} + \hat{u}\, e^{i\omega t}$ past an aerofoil at incidence α which occurs in the experiments described here. The result for the lift coefficient is

$$C_L = 2\pi\alpha\left[1 + \hat{u}/\bar{U}(C(k) + 1 + \tfrac{1}{2}ik)e^{i\omega t}\right] \tag{3}$$

where the Theodorsen function

$$C(k) = \left[J_1(k) - iY_1(k)\right]/\left[J_1(k) - iY_1(k) + iJ_o(k) + Y_o(k)\right]. \tag{4}$$

In the present case $\hat{u}$ varies with x over the acoustic wavelength, but since this is very large compared with the aerofoil chord this variation may be neglected and $\hat{u}$ treated as a constant amplitude.

The factor 2π in equation (3) is the theoretical lift curve slope for a very thin aerofoil. A better agreement with experiment is obtained by replacing it by the measured lift curve slope a_o of the aerofoil. Thus:

$$C_L = a_o\alpha\left[1 + \hat{u}/\bar{U}(C(k) + 1 + \frac{i\pi}{a_o}k)e^{i\omega t}\right]. \tag{5}$$

4. DISCUSSION OF RESULTS

4.1 Attached Flow. A plot of mean lift coefficient against incidence for the NACA 0012 aerofoil obtained from overall lift measurements and integrated pressures is given in Figure 6. These show that at 10^o at this Reynolds number (1.2×10^5) the flow is attached and the mean lift curve slope up to this incidence is approximately 5.4. Flow visualisation with oil and chalk shows that a separation bubble is present. The mean lift coefficients at this incidence are also effectively unchanged by the addition of an oscillatory flow. Figure 7 shows the variation

(5) Morfey, C.L. Lift fluctuations associated with unsteady chordwise flow past an aerofoil. ASME Journal of Basic Engineering D92, p663, 1970.

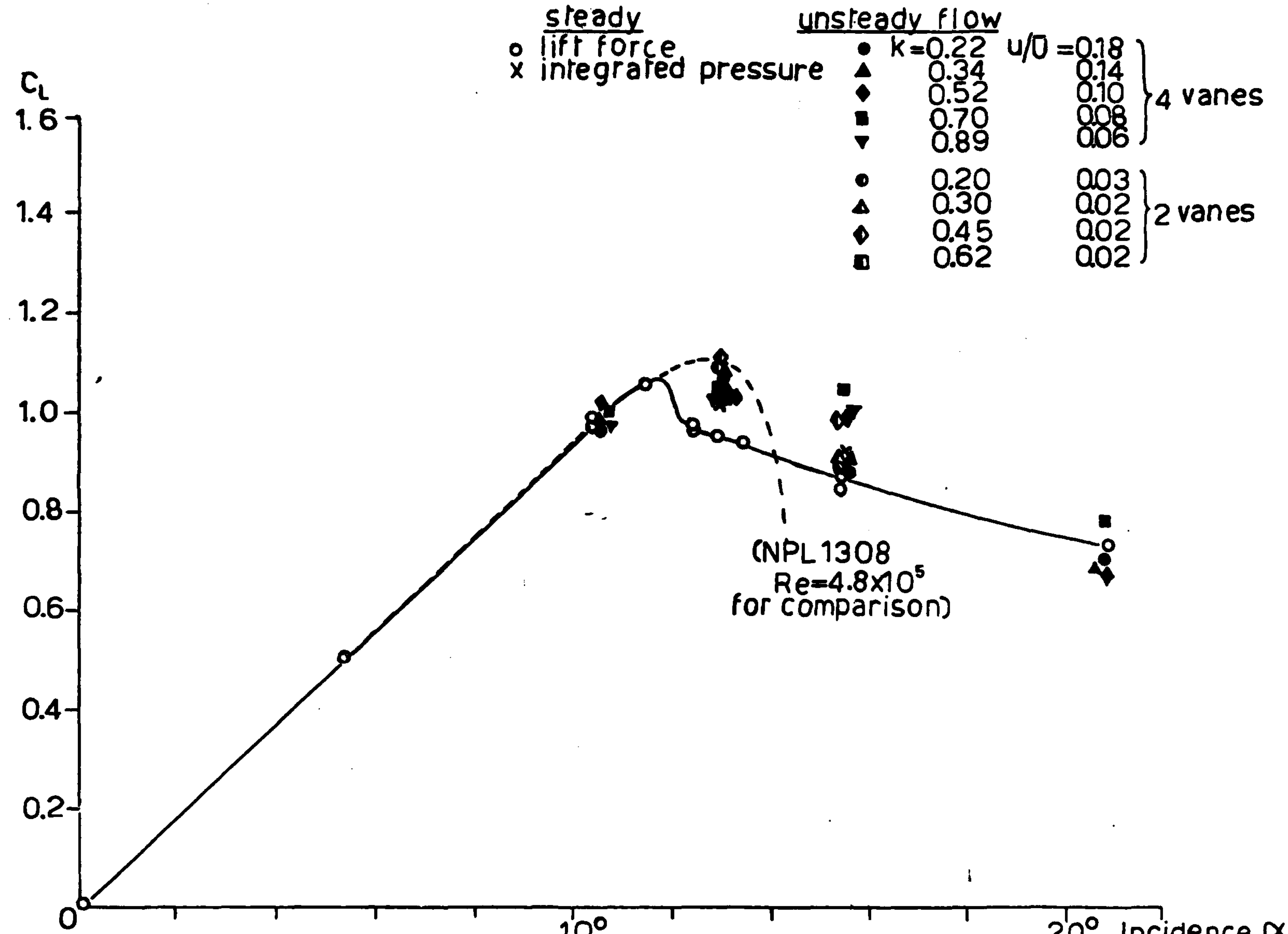

FIGURE 6

Mean lift coefficient in steady and unsteady flow.

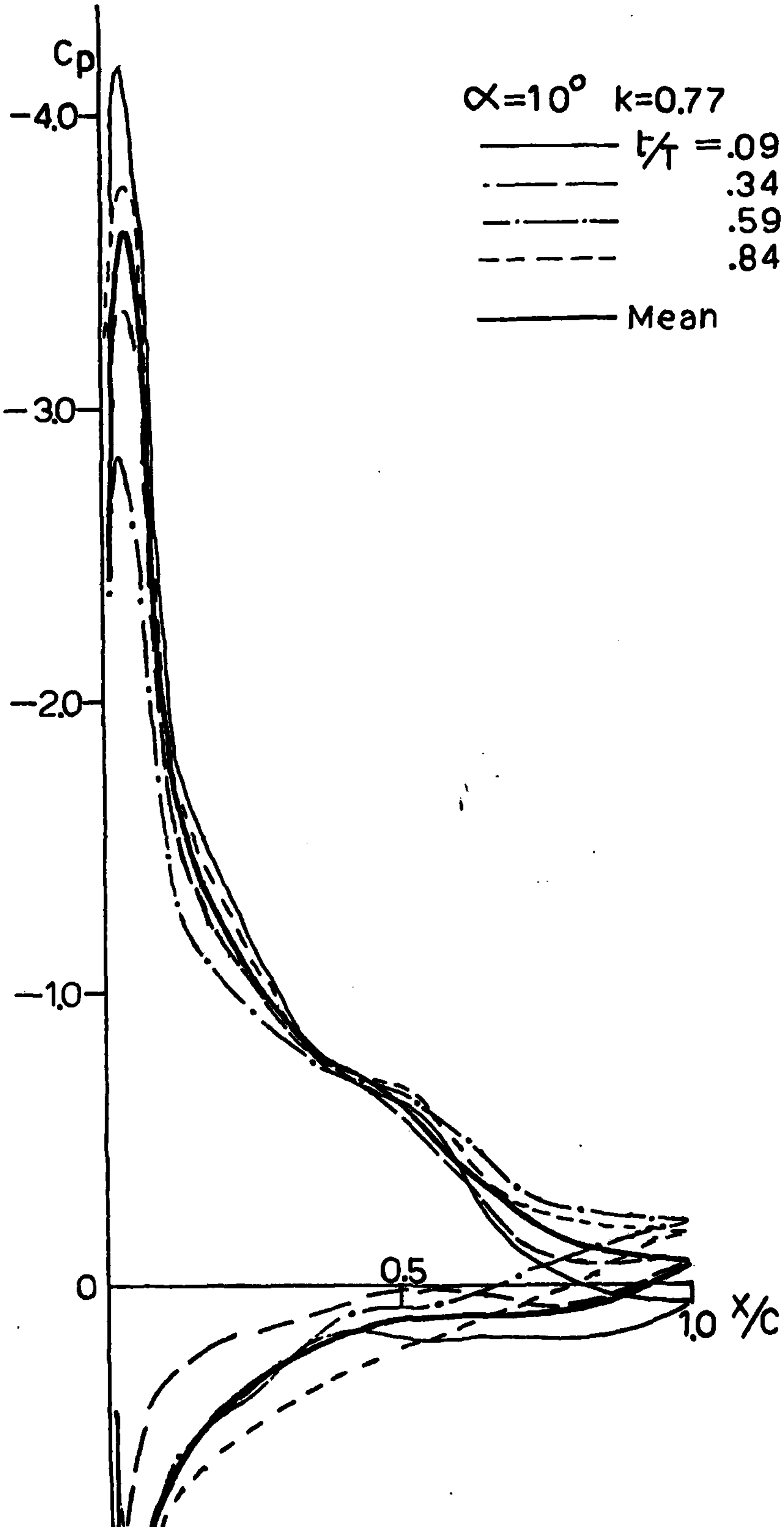

FIGURE 7

Cycle averaged pressure coefficients at different phases of the cycle for attached flow.

of attached flow pressure distribution through the flow cycle at a reduced frequency $k = 1.0$. In the same figure a comparison of the variation of lift coefficient through the flow cycle with the thin aerofoil theory (equation 5) shows good agreement. Similar results were obtained at lower values of reduced frequency and for lower oscillation amplitudes. Figure 8 shows both the minimum and maximum of the lift coefficients over each flow cycle compared with the theoretical prediction for $\alpha = 10^o$. In general both experimental methods of obtaining the lift coefficient, that is by overall lift measurement and by integrated centre-line pressures are in good agreement with each other and with the theory. The centre-line pressure results are very slightly higher than the overall lift result probably as a result of the fall off in lift close to the end plates due to the effects of the small end gaps, the end plate boundary layers and a small effect of trailing vorticity.

4.2 Separated Flow. The curve of lift coefficient against incidence given in Figure 6 shows that in the present series of experiments (Re 1.2×10^5, R.M.S. free stream turbulence = 0.9%) the NACA 0012 aerofoil stalled at an incidence just less than 12^o. In nearly all cases the integrated centre-line pressures gave rather higher separated lift coefficients than the overall lift measurements. This can be attributed to the three-dimensional nature of the separated flow and its interaction with the endplates. Figure 6 also shows the mean, and Figure 8 the extreme values of the lift coefficient averaged over a number of cycles of oscillatory flow for aerofoil incidences of 12.5^o, 15^o and 20^o. Two points are immediately obvious from these results.

(i) The presence of oscillations in the free stream tends to increase the mean lift coefficient, the biggest effect occurring when the reduced frequency is greater than 0.5.

(ii) The maximum lift coefficient is frequently well above the lift coefficient for attached flow at the same incidence, assuming a continuous lift curve with constant slope.

In general the lift fluctuations are much larger than those predicted by linear theory. However at 12.5^o incidence a fair correlation is obtained for the peak lift coefficient in a cycle by adding the effect due to the oscillatory component of the velocity calculated by the linear attached flow theory to the curve A for mean attached flow lift. There is a similar correlation between the minimum lift coefficient and that obtained by subtracting the linear attached flow result from the minimum lift coefficient occurring for separated flow in a steady incident stream. The same result, Figure 9, can be demonstrated for lower amplitudes of oscillation. This suggests that the flow is oscillating between approximately fully attached and fully stalled conditions at this incidence.

The same result also occurs at 15^o for the higher reduced frequency of oscillation ($k > 0.5$) at the larger amplitudes (Figure 8). However for the lower reduced frequencies or lower amplitudes of oscillation (Figure 9) the flow appears always to be at least partially separated, with maximum lift coefficients well below those which would be predicted by this simple hypothesis.

At 20^o the flow appears separated over the whole range of amplitudes and frequencies tested.

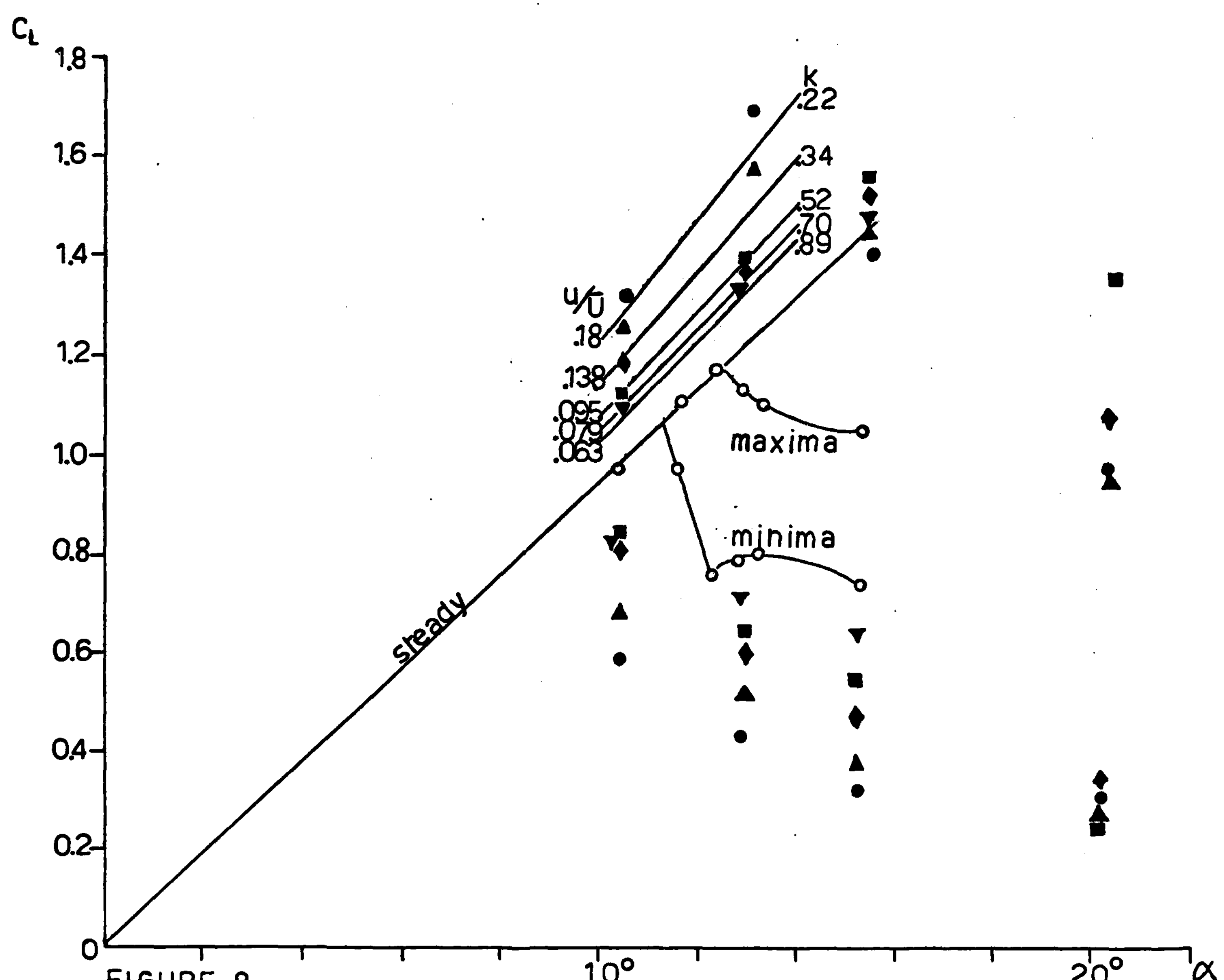

FIGURE 8 Maximum and minimum values of lift coefficient for larger amplitude unsteady flow. ——— Result from thin aerofoil theory.

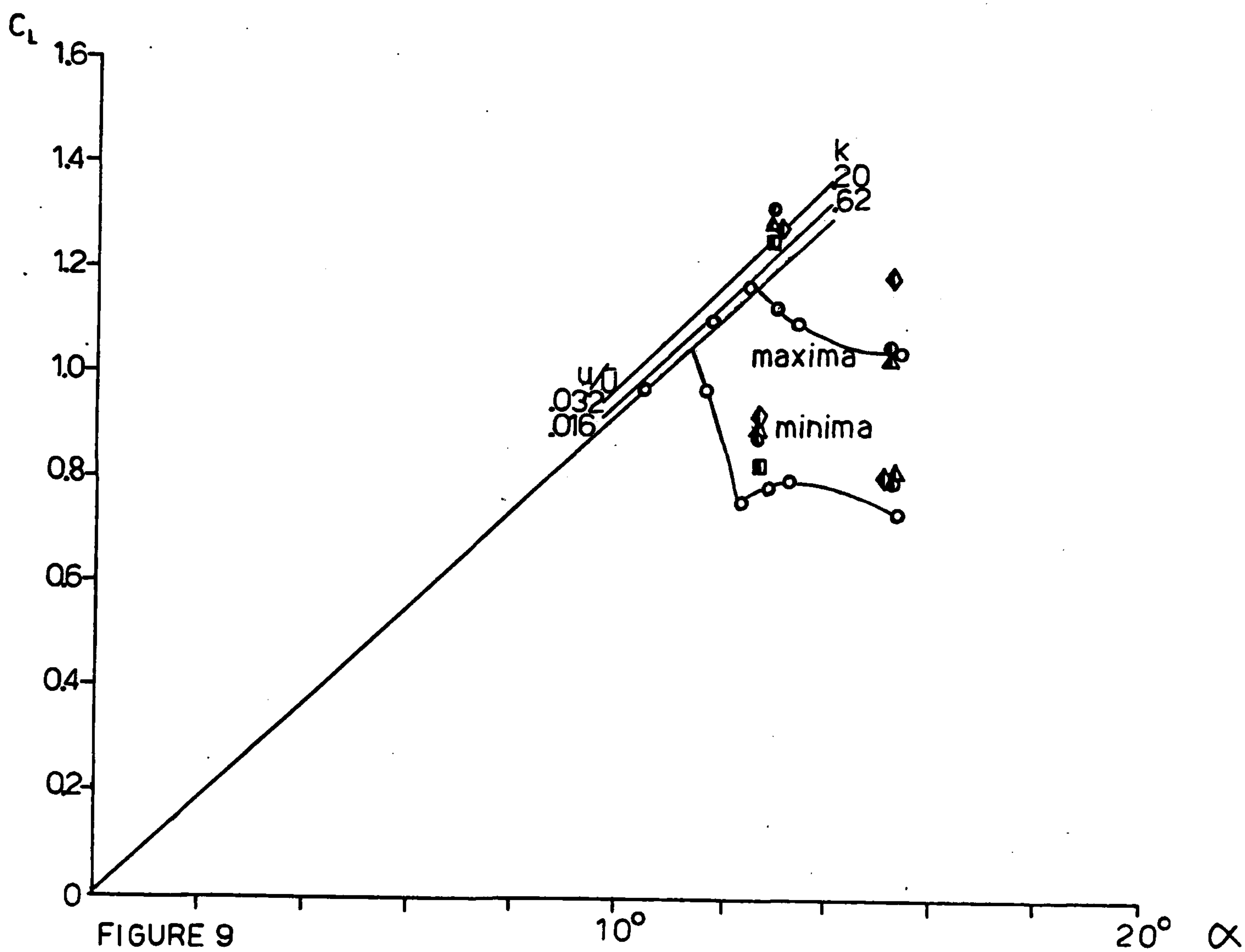

FIGURE 9

Maximum and minimum values of lift coefficient for smaller amplitude unsteady flow. ——— Result from thin aerofoil theory.

Figure 10 shows mean and fluctuating pressure distributions for $\alpha = 15^{o}$ and $k = 0.22$, and Figure 11 the same for $k = 0.71$. The former case shows a quasi-steady response to the oscillatory flow in which the upper surface appears to remain fully separated. But in the case of the higher reduced frequency the upper surface pressure distributions are greatly changed. This marked difference between high and low reduced frequencies was also found in a similar experiment carried out on a NACA 0012 aerofoil by Saxena et al (2, above) at a higher Reynolds number (2.5×10^{5}). Quite high suction peaks are obtained near the leading edge, but the pressure distributions do not indicate fully attached flow but rather that the separated shear layer may be following the surface quite closely. In addition there is evidence of a suction peak associated with a shed vortex moving rearwards over the aerofoil surface during the reduced velocity part of the cycle. The apparent convection speed of this vortex is in the range $0.5\ \bar{U}$ to $0.6\ \bar{U}$. Flow visualization (Figure 5), shows some evidence of an organised structure moving over the rear surface of the wing in the case of flow at a large value of reduced frequency (1.3) when compared with steady incident flow at the same Reynolds number.

When the wing was placed at an angle of incidence of 12.5^{o} which was just greater than the incidence for steady stall at this Reynolds number the lift and pressure distributions exhibited a considerable random variation from cycle to cycle which was not so apparent at higher incidences. An example of this is shown in Figure 12 where it appears that the lift is fluctuating between an effectively attached value for one flow cycle to a separated variation in the next. This conclusion is reinforced by the good agreement between the peak lift coefficients measured, which occurred in attached flow cycles and the predictions of unsteady (attached flow) thin aerofoil theory. It was found that the type of cycle which occurred could be correlated with the velocity signal of a hot wire placed just above the surface and behind the estimated separation point at the position ($x = 0.053c$, $\delta y = 0.015c$). An example of this is also shown in Figure 12 and it can be seen that peaks occur in the velocity trace associated with the high speed part of the attached flow cycle. A deep trough is present in the separated flow cycle since the hot wire is now in the separated lower velocity region. This signal could therefore be used as an effective discriminator between the two types of cycle. The computer program described earlier contained a section to perform conditions averaging of cycles according to this discriminator.

Oil and chalk measurements indicated that the separation line on the aerofoil at 15^{o} incidence and the Reynolds number 1.2×10^{5} of the tests, was at approximately 0.02c from the leading edge. The aspect ratio of the aerofoil section between the end plates was approximately 3 and two main separation cells were observed to occur on the upper surface. Stalling was of the leading edge type caused by a short bubble failing to reattach. The presence of an unsteady incident flow did not appear to alter the position of the separation line significantly although it did tend to induce a straighter line, probably due to the correlating effect of the unsteady flow on the rolling up of the separated shear layer.

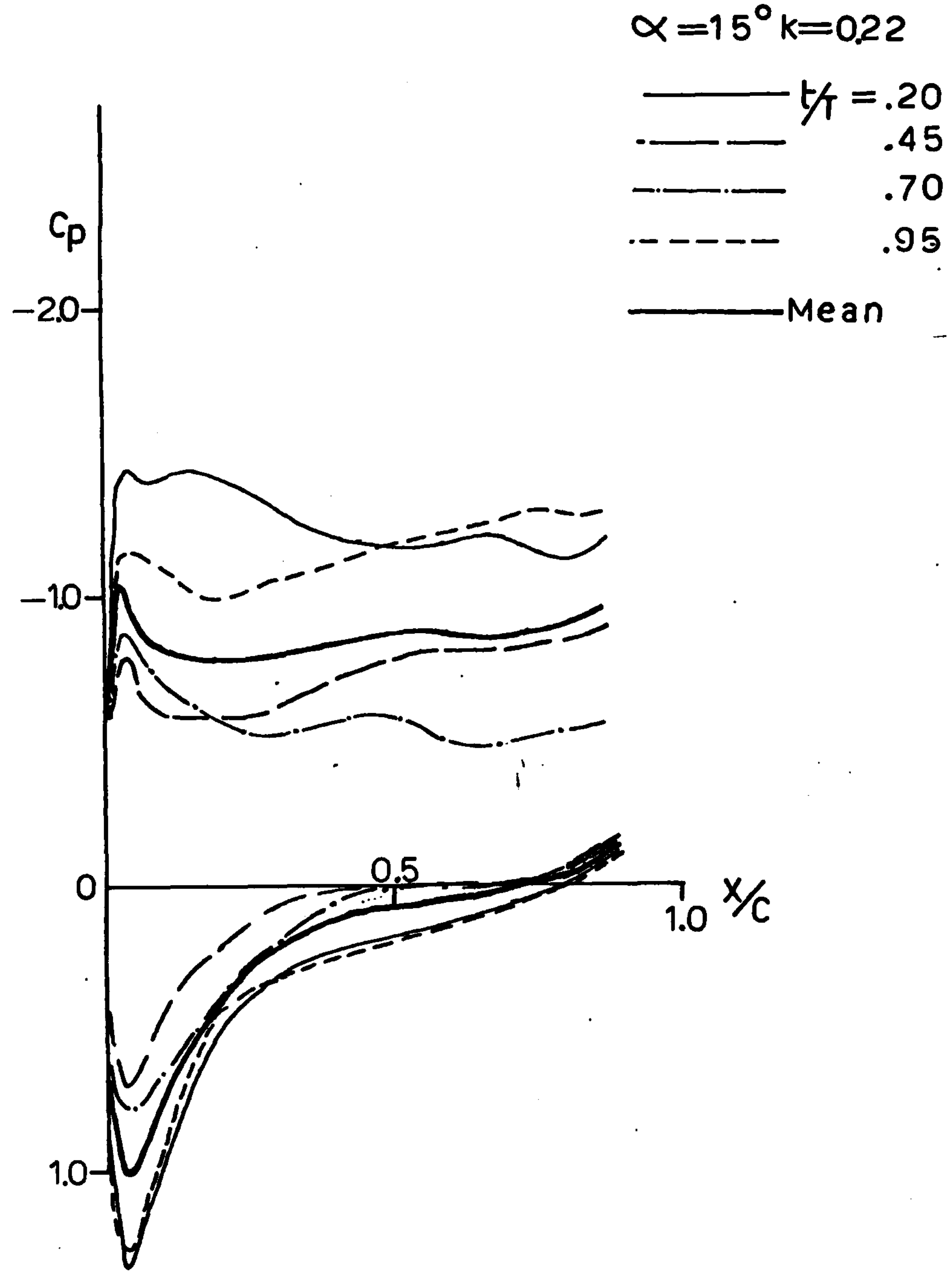

FIGURE 10

Cycle averaged pressure coefficients for separated flow, unsteady free stream at low reduced frequency.

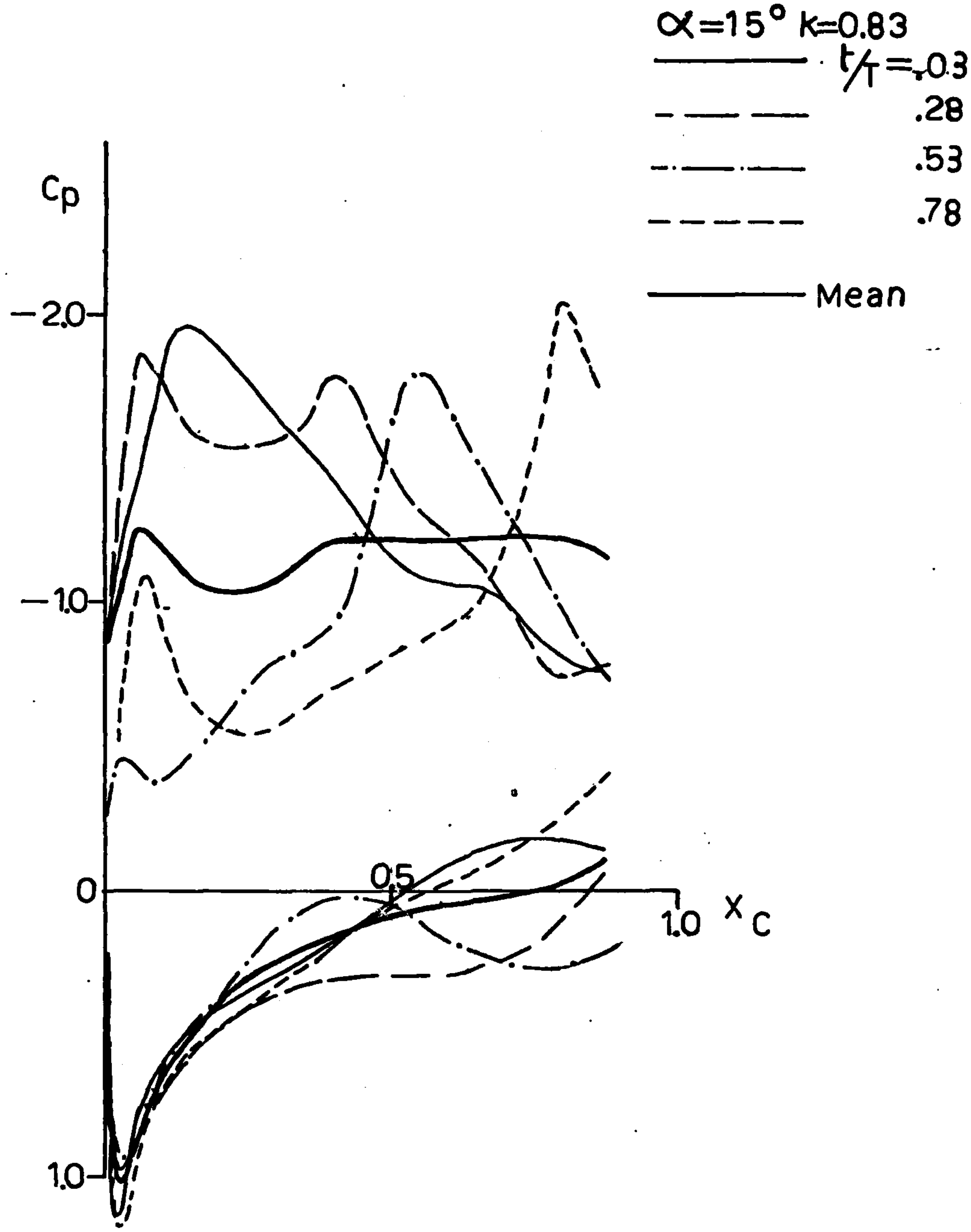

FIGURE 11

Cycle averaged pressure coefficients for separated flow, unsteady free stream at higher reduced frequency.

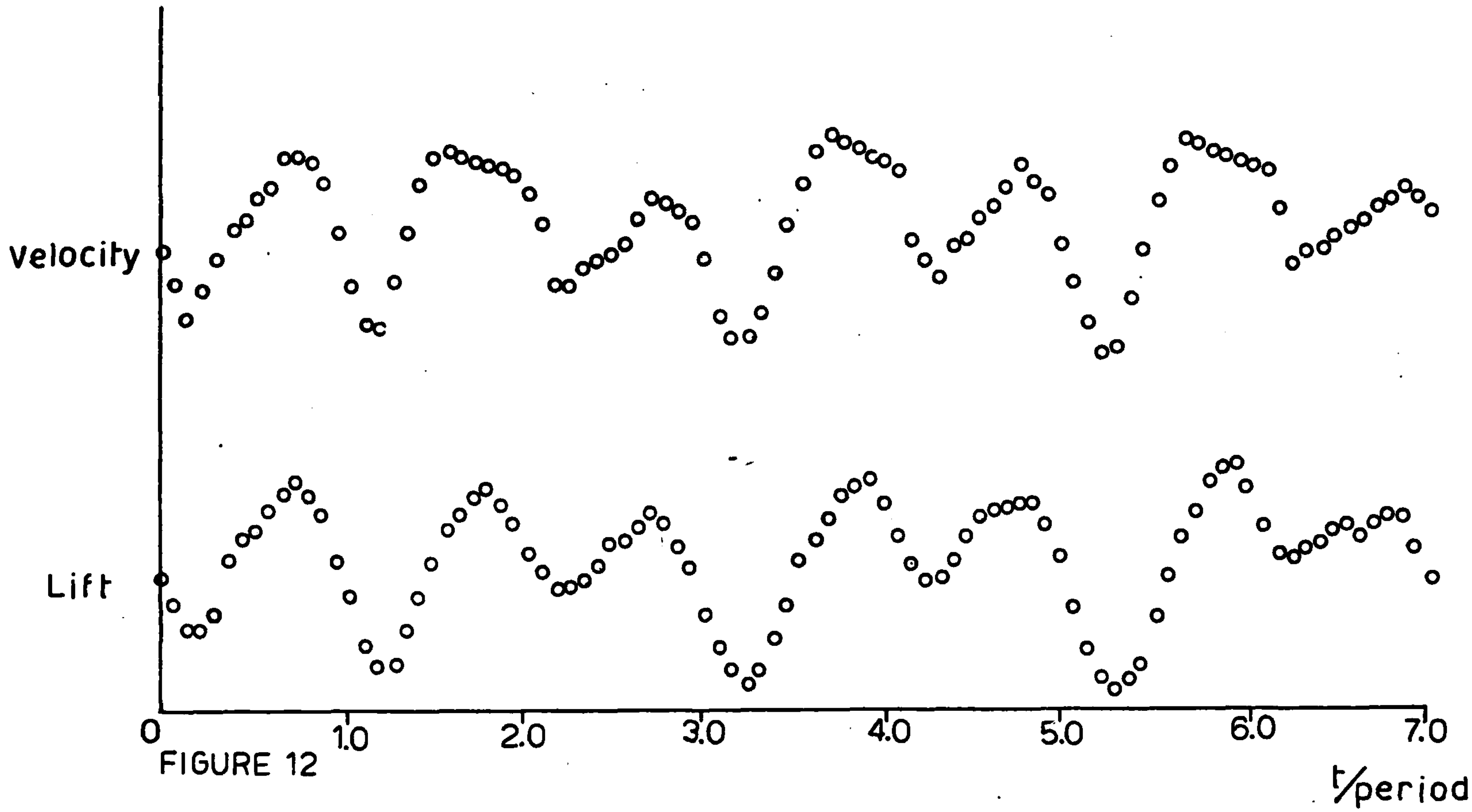

FIGURE 12

Time histories of lift force and near surface velocity for separated flow, $\alpha = 12.5^{\circ}$, $k = 0.52$.

A discrete vortex calculation for both attached and separated flows over aerofoils has been developed parallel to the experimental work described in this report. This calculation is based on the Cloud-in-cell vortex method (see for example 6). Vortices are released from the trailing edge, satisfying the Kutta Joukowski condition and in the case of separated flow from a specified point supplied from measurement of the front separation position. The calculation is carried out by transforming the aerofoil to a circle and solving for the velocity field due to the free stream and the vortices on a regular circular mesh. A fast Fourier transform is used to solve Poisson's equation for the stream function on the mesh.

The results of such a calculation for a 12% thick Joukowski aerofoil with the front separation point fixed at 0.02c are shown in Figure 13 compared with steady flow over the NACA 0012 aerofoil with a similar separation position. Further calculations are currently being carried out to compute the cases of unsteady free stream flow described in this report.

5. CONCLUSIONS AND RECOMMENDATIONS

A series of experiments on attached and separated flow over aerofoils in a free stream with a sinusoidal streamwise perturbation have been carried out.

Pressure and overall lift force measurements for incidences less than the stall agree well with the predictions of unsteady thin aerofoil theory to the accuracy of that theory.

For the case of separated flow over the aerofoil two different types of flow regime were found. For a given angle of incidence above the stall incidence for steady flow, combinations of small oscillatory flow amplitude or low reduced frequency gave flows which exhibited quasi-steady behaviour with the pressure distribution retaining a fully separated form. However when the amplitude or reduced frequency were increased above certain critical values the whole upper surface flow changed. The pressure distribution and flow visualization showed the passage of a strong vortex formed by a rolling up of the separating shear layer behind the leading edge. The vortex appeared to be convected at about half the free stream speed over the upper surface. Higher amplitudes of fluctuation and peak lift coefficients were induced on the aerofoil than in the quasi-steady case. There was a moderately good correlation between the peak lift coefficients and values predicted by attached flow thin aerofoil theory. The minimum values of the lift coefficients were below the minimum lift coefficients occurring in steady incident flow by a similar amount.

The critical values of amplitude and reduced frequency of gust to cause a change-over between these two types of flow increased as the incidence above the stall increased. At incidences close to the mean stall the influence of the incident oscillatory flow was to cause the upper surface to reattach spasmodically for whole flow cycles, while remaining separated for others. The different regions of flow are summarised in Figure 14.

(6) Leonard, A. Vortex methods for flow simulation. Journal of Computational Physics Vol.37, p.289, 1980.

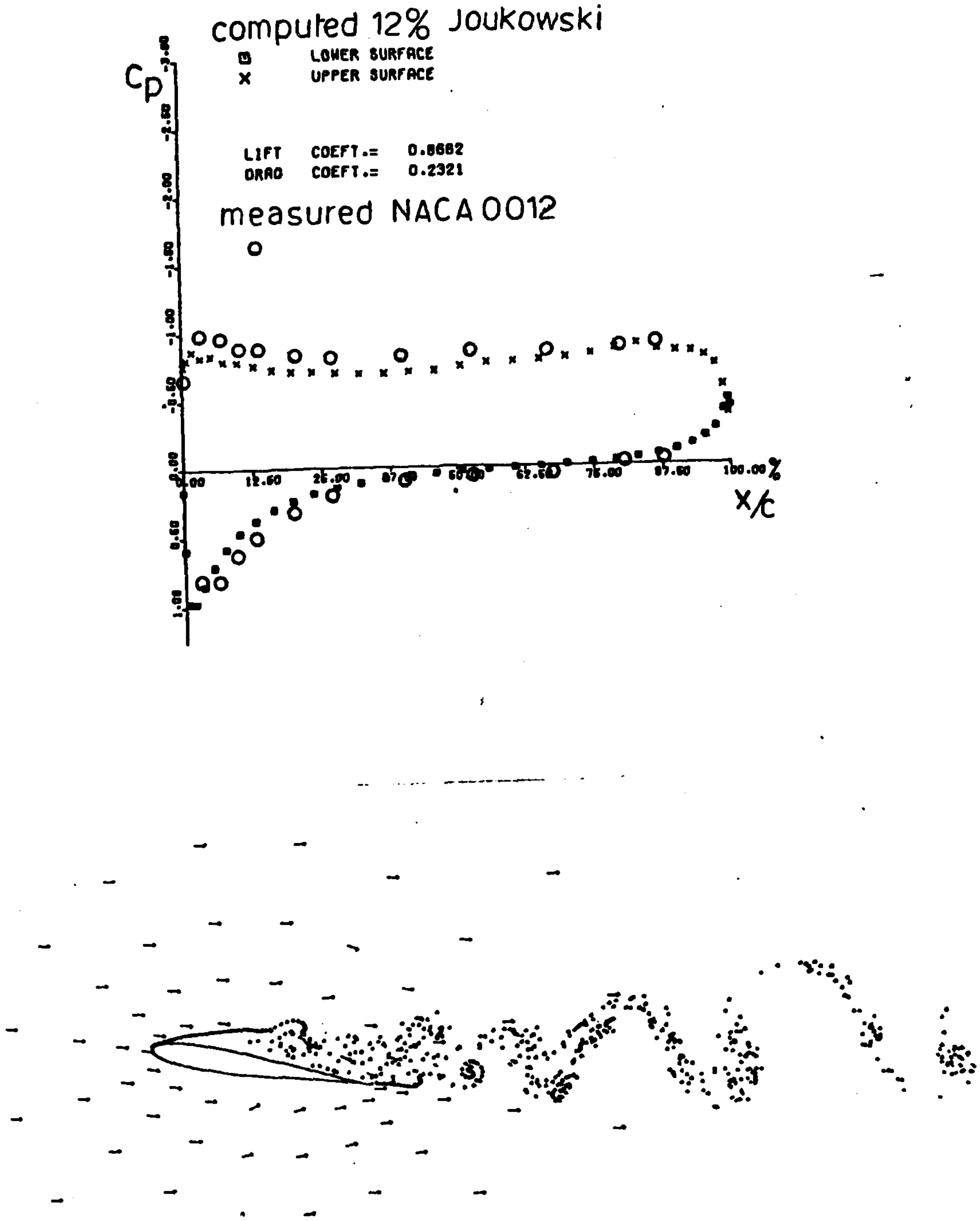

FIGURE 13

Example of mean pressure coefficient and vortex wake predicted by discrete vortex calculation for $\alpha = 15^{\circ}$.

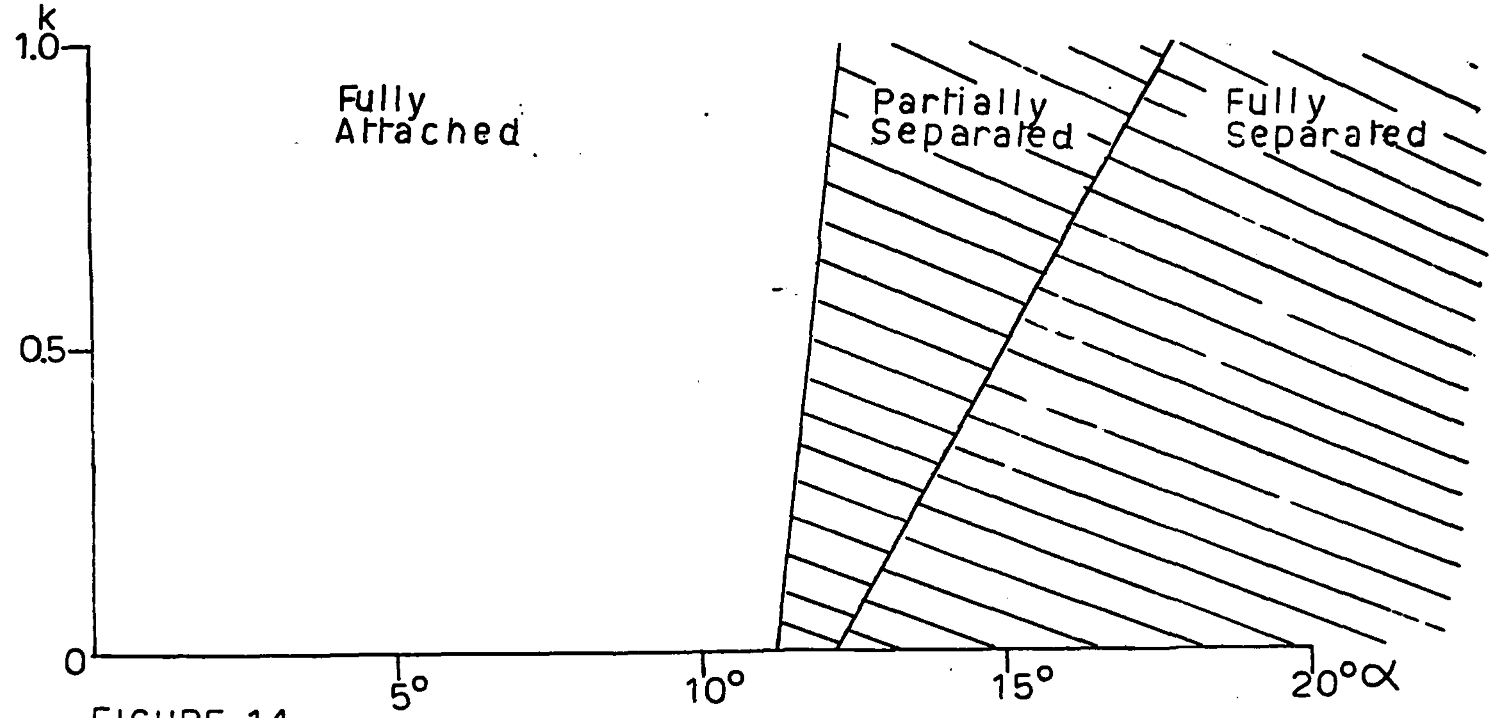

FIGURE 14

Approximate regimes of separated and unseparated flow.

It is difficult at present to extend the type of investigation described in this report to significantly higher Reynolds numbers (i.e. increased by a factor of 10 or more). Further fundamental experiments on a separation shear layer in this type of flow could be performed at much higher Reynolds numbers only if large wind tunnel constraints were accepted as a part of the experiment, or by using an oscillating aerofoil in a larger steady flow wind tunnel. Work with oscillatory gusts also has relevance to the interaction of a wake from upstream with the separating flow on a wing or aerofoil. This can occur both for interference flows on aircraft and in aero-engine compressors and might be more easily simulated at higher Reynolds numbers in a wind tunnel, using a representative moving wake.

The relevant reduced frequencies of helicopter rotors are sufficiently low to indicate that the effect of streamwise oscillations (alone) of the relative velocity of the flow to the blade should be expected to lead to the quasi steady type of separated flow, except very close to the stall angle. This is in contrast to the effect of pitching oscillations passing through the mean stall incidence.

6. REFERENCES

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